Penalty for Fuel Economy – System Level Perspectives on the Reliability of Hybrid Electric Vehicles During Normal and Graceful Degradation Operation

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***Abstract*— Generally people tend to think only in terms of fuel economy and additional cost premium on vehicle price while discussing about hybrid electric vehicles (HEV). This paper tries to emphasize that the overall acceptability of a vehicle also has to do with its system level reliability. It discusses the issue of system level reliability in hybrid electric vehicles from a quantitative point of view. It also introduces a quantitative meaning to the concept of graceful degradation and mode of operation under graceful degradation condition. All these are discussed in stages, starting from a regular internal combustion engine based vehicle, and later transition of those to hybrid electric vehicles. The paper intends to drive the point that in HEV, one of the penalties for fuel economy that has to be paid comes in terms of reliability.**

***Index Terms* — hybrid electric vehicle, HEV, power electronics, inverter, motor, multiplex system, CAN controller.**

I. INTRODUCTION

Hybrid electric vehicle system is considered as an important technology in the automotive industry these days. This is due to the concern for fuel economy, worldwide uncertainty in energy supplies, and pollution control. While discussing the subject, it seems that the focus in the technical community and the literature has been primarily on the above items and also on the control of the electric motor drives [1- 4] related to HEV. In addition, people also think in terms of cost premium, i.e. how long it takes to recover the extra cost of the vehicle (compared to a regular non-hybrid vehicle) [1- 4]. Various figures have been indicated in the media and elsewhere in the technical community, suggesting that it can take anywhere from 5 to 7 years to recover the extra cost of a HEV through any potential fuel savings. However, very little is known to have been discussed about the issue of overall vehicular system reliability in HEV. The issue is not trivial and the overall acceptability of these vehicles in the long run will significantly depend on that, in addition to merely fuel economy and extra cost recovery. This paper tries to bring this issue of system reliability to the attention of the technical community and discusses the same from a quantitative point of view. The intention here is to drive the point that in HEV, one of the penalties for fuel economy that has to be paid, comes in terms of reliability. It emphasizes that a HEV is not merely a collection of multiple propulsion sources and control system to extract better fuel economy, rather it has a whole plethora of items in it, and that the overall system level reliable functionality is no less important in making a HEV operate and making it acceptable to the consumer in the long run, rather than only the concern for fuel economy and cost. Unfortunately, literature on this topic is not available anywhere in the public domain to the best of the knowledge of this author. Only two papers [5, 6], indicated in the reference on a similar topic but for analyzing a different system, are also by this author and other co-authors. The primarily reason for this, in the opinion of this author, is that, in connection with hybrid vehicles people have been predominantly involved until now with only its drive and control technology, and matters related to fuel economy. The second reason is that the hybrid vehicle technology is relatively new, and not much information about its reliability exists in the industry yet. The other important reason is that reliability data of components and subsystems takes long time to monitor and collect, and even if it is conducted in the industry, they are normally retained as proprietary information. It is emphasized here that this paper is not intended to contribute towards HEV technology development, rather, its purpose is to study the system level reliability from a user's perspective.

The paper discusses vehicular reliability issues, using the architecture of a regular IC engine based vehicle, followed by series and parallel HEV architectures. The overall subsystem and component level reliabilities are introduced by using some assumed numbers for reliability, and then analyzing the same. Later, the concept of graceful degradation is introduced and its implication from a quantitative point of view is discussed. The numerical values of reliability used in the paper are merely to illustrate concepts, and the exact reliability situation will depend on the system architecture and precise values of the reliability numbers involved in the system under study. The main intent of the paper is to describe a methodology for evaluating system level reliability in HEV systems, so that a proper trade-off study can be made between various systems during design stages. Furthermore, since a system or subsystem is composed of various constituent components, an accurate reliability of the overall system will not only

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depend on those individual component reliabilities, but also on how those components are connected i.e. the architecture used to make the final system [5, 6]. Of course, it should be recognized that finding accurate reliability numbers for various components in a system require prolonged efforts, sometimes modeling and simulation studies, and also experimental tests; and these issues are not within the scope of this paper.

II. SYSTEM LEVEL ARCHITECTURES IN HYBRID ELECTRIC VEHICLES

Architectures of hybrid electric vehicles are quite well known [3-4]. It consists of multiple propulsion systems i.e. an internal combustion (IC) engine and also an electrically driven propulsion system with peripheral controls. The electric propulsion system is driven by appropriate power electronics, connected to a source, i.e. typically a battery which can be charged by running the electric drive in generation mode, or discharged while providing drive power (in motor mode) to the wheels. The IC engine and the electric propulsion system also need various controllers, which have to coordinate between themselves. All these involve microcontroller or digital signal processor applications, and computer communications realized through CAN (**C**ontroller **A**rea **N**etwork) or other kinds of communication systems and protocols. These communication systems are also sometimes designated as multiplex systems [5, 6].

A possible system level architecture of a hybrid electric vehicle is shown in Figure 1. As can be noticed, it consists of several controllers, namely, battery or storage (or can be a fuel cell based system as well) controller, brake controller, vehicle system controller, HEVPT (i.e. HEV power train) controller, IC engine controller or electronic engine controller (EEC, also sometimes called ECU or Electronic Control Unit), other controllers as needed, depending on the specific vehicle involved and depending how the designer decides to implement those, and a number of auxiliary load controllers. The list included above can vary depending on the architecture and design used, and is not exhaustive. In addition, it should be noted in connection with load controllers that sometimes a group of loads may be controlled by a single controller. And of course, there are a number of sensors associated with various loads, battery, motor drives, brakes and other items. Many of these controllers have nothing to do with high voltage propulsion operation, and use low voltages (like 12 volts, 24 volts etc., depending on the vehicle involved). Controllers related specifically to propulsion subsystem or components are involved with high voltages.

III. RELIABILITY ANALYSIS OF HYBRID ELECTRIC VEHICLE ARCHITECTURES

For a system level perspective in studying the reliability of HEV, it is necessary to trace the individual reliability values of the subsystems and components noted in Figure 1 [5, 6]. However, the discussion can be made simple by considering the simplified version of the above, and redrawing the three different architectures, i.e. regular IC engine based vehicle, series HEV, and parallel HEV, as shown in Figure 2, where one can still compare the system reliabilities of these architectures without taking a microscopic view of every single component in the system. Instead, one can perform the study by lumping individual component reliabilities within the various subsystems and assigning an overall reliability to these subsystems. These will be discussed in the following. Before continuing with the discussion, it will be worthwhile at this point to define some of the terminologies involved, which will be suitable for the purpose:

System: a collection of several hardware and/or software (components) integrated together and intended to perform an assigned function. A system will generally have input/output to interface with anything outside the system. If a system is doing its intended function exactly as intended, the system is said to be "fully" functional. In engineering system, and particularly in connection with the type of systems under consideration in this paper, it is possible for a system to perform some of its intended function, but not all. In that case it will be called a "partially" functional system, or a system in "degraded" mode. If a system is not functioning at all, i.e. not performing any of its intended functions, then it will called a system in "failure" mode or "fully" failed mode. Before transitioning from "fully" functional to "fully" failed mode, a system can go to a "degraded" mode with some amount of functionality, and in this case it will be said that the system is in a "graceful degradation" mode.

Subsystem: a subset of the system above, with input/output defined. A subsystem will interface with another subsystem within the larger system.

Component: constituent element of a system or subsystem, which can be considered to be an entity.

Reliability: probability that a component, subsystem, or a system is functional, i.e. performing its intended function at the end of a particular time period, without any change or maintenance activities done on it within that time period. Thus, reliability, for the purpose of this paper, is connected with both probability and a time span.

Availability: a system which has reliability equal to 1, will be said to be "fully" available. The term availability and reliability will be used interchangeably in this paper from time to time for the convenience of discussion. If the reliability is less than 1, then its availability will also be less than 1.

For the purpose of this paper, the above terminologies should be sufficient, without trying to define these terms more microscopically.

Based on the previous terminologies, and using the various architectures in Figure 2, one can study the overall system reliability of each of these subsystems as follows. Consider the various items (subsystems) in Figure 2, and let the reliability of each of those be as shown in Table I:

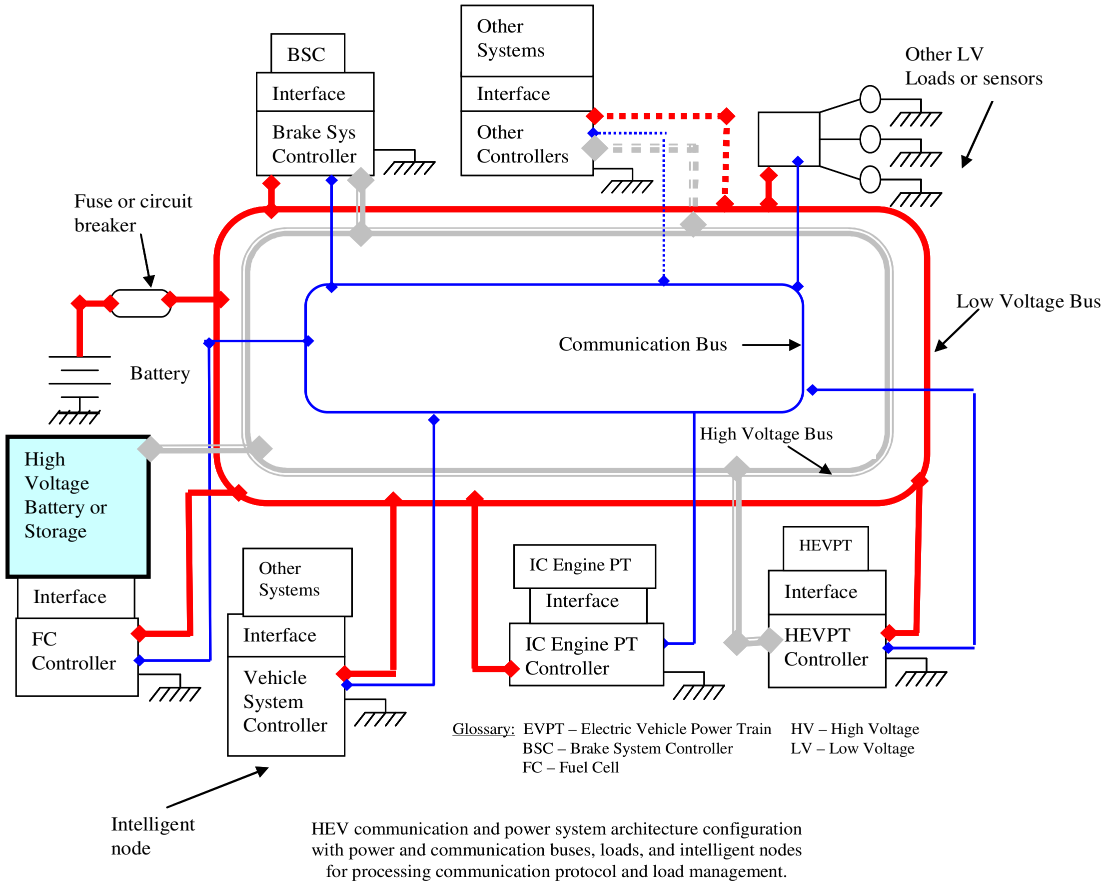
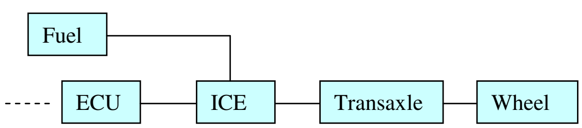
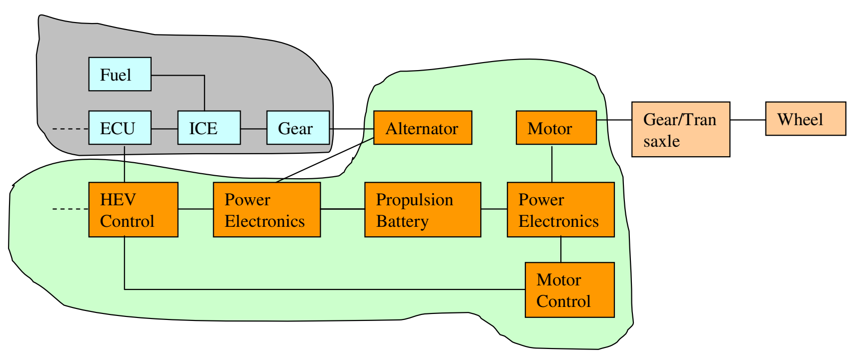


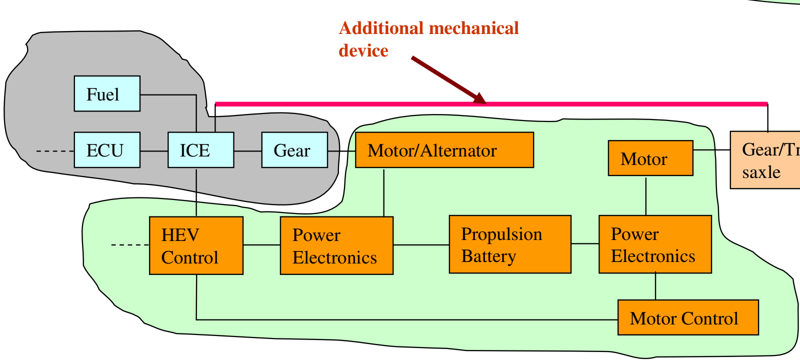
Figure 1. An automotive multiplex system architecture configuration with power and communication buses,



(a) Regular IC Engine Propulsion



(b) Series HEV Propulsion



(c) Parallel HEV Propulsion

Figure 2. System level block diagrams for : (a) Regular IC engine, (b) Series HEV, and (c) parallel HEV architectures.

Table I.

Subsystem/Component	Reliability
Fuel System	0.9999
ECU	0.99999
ICE	0.9999
Transaxle	0.99995
Wheel system	0.9999
Gear	0.99995
Alternator	0.99995
Motor	0.99995
Power electronics	0.99992
Propulsion battery	0.9999
Motor control	0.99999
HEV Control	0.99999

It should be noted that each of the above items are constructed by using a lot of constituent subsystems and components. However, one can use a single cumulative reliability number for each of the items above, e.g. for the motor an overall reliability of 0.99995 can be used, rather than delving into the individual constituent components within the motor.

The numbers above are used only for the purpose of illustration of the concepts in this paper. As noted earlier, component level reliability numbers are generally kept as proprietary items by the manufacturers. Hence obtaining exact numbers can be extremely difficult, if not impossible. The other issue is that these numbers can vary quite a bit from one manufacturer to another. Hence during architectural studies in the design phase, one need not be extremely tied up in trying to find exact numbers for various reliabilities. Rather, one should try to arrive at a broader picture of reliability of the system. Hence to perform a conceptual study one can use some tentative numbers to begin with, which can be replaced with any exact numbers one can obtain later on. Generally the best way to decide these tentative numbers, in the absence of specific manufacturer data, will be to estimate how many times over a time period or length of mileage one needs to repair the system (or subsystem, or component). Or, alternatively, over the same length of time or mileage, out of a certain number of a particular vehicular system/subsystem in service, one can estimate how many required repair.

Using the definition of reliability given earlier, it is now possible to study the system as follows. The numerical values indicated against each item above mean that at the end of a given (or chosen) period of usage time or mileage of the vehicle (may be 100000 miles e.g.), when the reliability is assigned a value, say, 0.9999 for ICE as an example, it means that the chance of its failure is 1 in 10000 (within that mileage or usage time starting from when the item was newly installed). It is true that reliability is a function of time as the system ages. However, it will be assumed to be constant for the purpose of the discussion in this paper, which will not affect the overall findings presented. For the purpose of this paper a worst case scenario reliability number will be considered, i.e. the probability that a system is fully functional at the end of a specified time period (or some predefined mileage etc.).

Since ultimately it is the wheel which is driven in a vehicle, hence wheel will be considered to be the final system load. Thus, the probability that the load is available or functional, is given by the followings, recognizing that for success or full functionality, all the subsystems must be working properly:

(a) For Regular IC Engine Propulsion:
Product of all the reliability terms corresponding to the architecture shown in Figure 2(a) (and using Table I), leads to:

$$R_{ICE} = \prod_{i=1}^{5} \lambda_i = 0.99964004849705 \qquad (1)$$

where R_{ICE} is the reliability (or the probability of being available) of the complete ICE vehicle system. Here the individual subsystem reliability values in Fig. 2(a) are given by λ_i. In other words, with the chosen numbers, the chance of an overall systemic failure is about 36 in 100000 cases (or about 4 in 10000). So, it can be easily seen that with more and more items in the system chain between fuel system to wheel, the reliability can be substantially reduced.

(b) For Series HEV Propulsion:
Here, as per architecture in Figure 2(b), product of all the reliability terms above leads to:

$$R_{SH} = \prod_{i=1}^{13} \lambda_i = 0.999210280440917 \qquad (2)$$

where R_{SH} (reliability of series hybrid architecture) is defined in an analogous manner like R_{ICE} as before. In other words, with the chosen numbers, the reliability of this system is now .99921 instead of .99964 for a regular ICE based vehicle. Now there will be about 79 failures in 100000, instead of 36 for the regular ICE engine based vehicle.

(c) For Parallel Propulsion:
Here, as per Figure 2(c), the product of all the reliability terms above leads to:

$$R_{PH} = \prod_{i=1}^{14} \lambda_i = 0.999160319926895 \qquad (3)$$

where R_{PH} (reliability of parallel hybrid architecture) is defined in an analogous manner like R_{SH} as before. In other words, with the chosen numbers, the reliability of this system is now .99916 instead of .99964 for a regular ICE. So, there will now be 84 failures in 100000. It should be noted that in equation (3) the product contains 14 items, unlike 13 for the series architecture. This is due to the additional mechanical linkage in Fig. 2(c).

It should be noted that the difference in reliability between the various architectures can happen due to:

- the particular architecture chosen and how the various elements are combined together to construct the architecture.
- the nature of complexity of each subsystem or component involved.
- the precise numbers (values) used for reliability of the subsystems or components.

In the next sections further extension of the reliability concept introduced above will be made.

IV. CONCEPT OF RELIABILITY AND GRACEFUL DEGRADATION

Consider the parallel HEV propulsion in Fig. 2(c), where demarcation between the IC engine based and the electric propulsion based subsystems are shown using shaded areas. It was seen before that the reliability or overall availability number for only the ICE based vehicle is: 0.99964. For parallel HEV, the reliability number for only the ICE portion of the propulsion (excluding the final transaxle and the wheel etc.) is: 0.99974. The reliability number for the electric propulsion part is: 0.99962. The (wheel + transaxle) reliability is 0.99985. For convenience of discussion below, the electric propulsion part of the HEV system will be designated as "EVP" (for ***E***lectric ***V***ehicle ***P***ortion). Similarly, the term "ICE" will be used to indicate the ICE portion of the propulsion system.

So, the probability that:

a) Both ICE & EVP are good is:
   .99974 * .99962 = 0.99936

b) ICE good and EVP bad:
   .99974 * (1-.99962) = .00037984

c) ICE bad and EVP good:
   (1-.99974) * .99962 = .00025987

d) Both ICE bad and EVP bad:
   (1-.99974)*(1-.99962) = .0000000987763207

and the reliability of:

e) The wheel and final transaxle together = .99985

It can, of course, be immediately verified that (a) multiplied by (e) above is the same number as in the expression given in equation (3) earlier (accurate within six decimal points due to truncation of the higher decimal numbers).

Therefore, the probability of having "some" amount of system functionality available, during partial failure conditions (i.e. under graceful degradation), is given by the sum of the items above (i.e. items a) through c)) multiplied by the reliability of the wheel + transaxle subsystem, i.e.:

$$P_{GR} = (a+b+c) * (e) = 0.999849906238495 \qquad (4)$$

where P_{GR} is the reliability or probability of the system under graceful degradation, and a, b, c, and e in equation (4) are the reliability numbers corresponding to items a), b), c), and e) earlier (i.e. a couple of paragraphs prior to equation (4)). This implies that in a graceful degradable mode the system availability is higher than the situation when the partial availability or graceful degradation mode is not taken into account. It seems from (4) that the reliability P_{GR} (for a parallel hybrid vehicle) under graceful degradation mode is higher than a purely IC engine based vehicle. Is this analysis truly valid? A deeper investigation leads to the conclusion that there is some issue with the above rationale. The situation a) above, where both ICE and EVP are available, implies that full service and performance is available to the user of the vehicle. But situations b) and c), where either ICE or EVP available, but not both, give only partial service or performance to the user of the vehicle. In other words, graceful degradation mode does not give the full "value" of the propulsion system compared to when the ICE plus EVP are fully functional.

The situations b) and c) above will now be analyzed. Consider that with partial service, as in items b) or c) noted above, the "performance" or "acceptability" on a scale of 0 to 100%, will be only 40%, compared to the condition when full service (as in "a") above) is available. Thus, one can write as follows (the number 40% being a perceived value of functionality or performance to the user of the vehicle, and is chosen for illustration purpose only):

$$P_{HEV\_40} = (a + 0.4\,b + 0.4c) * (\text{reliability of final mechanical drive, wheel etc.}) = 0.99947 \text{ (for 40\%)} \qquad (5)$$

This perception factor (like 40% above) is subject to definition; but one possible definition can be in terms of the ratio of the vehicle's available output power during partial operational condition, to the output power when the vehicle is fully functional, under identical load conditions.

Thus, based on the above discussion, one can now define "graceful degradation probability" P_{GR} as follows:

P_{GR} = {(Probability of the system being normal and fully functional, i.e. corresponding to the item a) noted earlier) + (Performance perception index) * (Probability of availability of the system in partially degraded mode)}.

"Performance perception index" is determined by numbers like 40% etc. indicated above, and "Probability of availability of the system in partially degraded mode" is determined by the numbers in items b) or c) indicated earlier.

In general, therefore, if the functionality perception factor is X%, the expression for P_{HEV_X} will be:

$$P_{HEV\_X} = (a + X/100*b + X/100*c) * (\text{reliability of final mechanical drive, wheel etc.}) \qquad (6)$$

This leads to:

$$P_{HEV\_50} = 0.99953 \text{ (for 50\%)} \qquad (7)$$

$$P_{HEV\_60} = 0.99959 \text{ (for 60\%)} \qquad (8)$$

P_{HEV_70} = 0.99966 (for 70%) (which is about the same as regular ICE based vehicle); (9)
P_{HEV_80} = 0.99972 (for 80%) ; this last one for 80% is higher than ICE based vehicle.); (10)
P_{HEV_100} = 0.999849874257205 (11)

From the above, it can be seen that with the assumed numbers for reliability, until the functionality or service performance perception index is around 70% or higher, one cannot really get the overall system availability or reliability which will be equivalent to that of the regular ICE based (i.e. non-hybrid) vehicle. This situation can be termed as "reliability break-even performance point".

How can the performance perception index noted above be changed ? For that one has to revisit the definition of this term and how they came about in the first place. Note that the above numbers could change depending on the exact reliability numbers for the constituent components, architecture, and the design strategy adopted – e.g. where one wants to focus – does one want to make a relatively bigger ICE and a smaller EVP (electric motor) etc. In other words, for design optimization, one has now got some additional degrees of freedom to ponder about, if the overall reliability of the system is to be changed. So, the question is: why this predicament came about, and how can one really make use of the above numbers on reliability index? The situation can be explained as follows. When a HEV is designed, each of the propulsion parts, i.e. the ICE (only the IC engine based propulsion portion) and the EVP (only the electrical propulsion portion), -- each of these are not individually designed for carrying the full power of propulsion (in series HEV, however, the EVP has to carry the full propulsion power to the wheels). But in a regular IC engine based vehicle, the IC engine is relatively bigger (than the IC engine used in the case of a HEV), and is meant to carry the full power of propulsion. This means that by making the size/s of the ICE and the EVP in a parallel HEV bigger, it is possible to achieve higher functionality, even under graceful degradation mode. Hence, in that way one can increase the overall system level reliability. But doing so implies that the cost and size will increase, and here one will encounter an engineering challenge, while trying to optimize the reliability against cost and size. Size will impact packaging and space constraints, and also can affect cost. One can, of course, increase the reliability (and hence the overall system availability) by using higher quality components and products as well, which will definitely affect the cost. All the previous situations arise due to the fact that in a regular ICE vehicle, there are fewer components to go wrong from the reliability point of view. It should be noted once again that the issue is not being discussed here from fuel economy or similar point of view. The above study is being made here solely from a reliability standpoint.

There are some additional issues: e.g. if the EVP (the electrical propulsion of the HEV) in a parallel HEV fails, one can still run with the ICE and refill the gas tank as needed, and keep running at a lower performance. If the ICE fails one can run with the EVP, only until the battery lasts. Thereafter one can do a plug-in operation, if there is provision for that; otherwise there is no option. Here one must not run the battery below the level of allowable SOC (state of charge), to save the battery life.

Next, the situation for a series HEV will be considered. In a series HEV the alternator is driven by the IC engine, which then charges the battery. The battery is used to drive the electric propulsion motor through appropriate power electronics and control. In this architecture, i.e. the one in Figure 2(b), with shaded areas showing the demarcation between the propulsion systems run by the IC engine and the electric drive, if the IC engine fails then nothing much can be done, and the electric propulsion, which is the only means to drive the wheels, will be able to work until the battery is drained out to its SOC limit. On the other hand, if the electric propulsion system fails, then the whole vehicle system will fail, because the ICE is not mechanically connected to drive the wheels.

We saw before that the reliability or overall availability number for the regular IC engine based vehicle is: 0.99964. For Series HEV, the reliability of the ICE portion of the propulsion is: 0.99974. The reliability of the electric propulsion part is: 0.99962. The reliability of the final load portion (wheel + transaxle) is 0.99985.

In view of all the above, the reliability value b, corresponding to item b), noted earlier in this section (i.e. corresponding to the condition ICE good, EVP failed), should be assigned 0.

Note that for the fully functional series HEV, the reliability or availability is given by equation (2), which gave a value of 0.99921. Hence, in an analogous manner as in the case of parallel HEV, for the series HEV also one can derive the availability under graceful degradation as follows. If P_{HEVS_X} is the availability when the perception factor for performance in percentage is X, under graceful degradation conditions one can write:

P_{HEVS_X} = (a + X/100*b + X/100*c) * (reliability of final mechanical drive, wheel etc.) (12)

This leads to:

P_{HEVS_40} = 0.99931 (for 40%) (13)
P_{HEVS_50} = 0.99934 (for 50%) (14)
P_{HEVS_60} = 0.99937 (for 60%) (15)
P_{HEVS_70} = 0.99939 (for 70%) (16)
P_{HEVS_80} = 0.99942 (for 80%) (17)
P_{HEVS_100} = 0.99947 (for 100%) (18)

In the above, b is assigned to be 0, and the reason for this was given earlier. Therefore, in this vehicle, unlike the parallel hybrid vehicle, one cannot achieve a break even point for availability due to the absence of the term containing b (which is 0). The reliability numbers for parallel and series vehicles, as indicated in equations (5) through (11) and (12) through (18) respectively are plotted in graphical form in Figure 3. This graph shows that at a

certain point the curve for the regular IC engine based vehicle, which is a straight line with a constant value of 0.99964 as per equation (1), intersects with the curve for the parallel HEV. This is the break even point between the two systems in terms of performance perception index. After this point the parallel HEV becomes better than the purely IC engine based vehicle in terms of reliability index. The series HEV is behind both the regular ICE vehicle or the parallel HEV. The break even point indicates that for a parallel HEV it is necessary to over-rate the propulsion systems to some extent, depending on how much performance once desires to achieve during graceful degradation i.e. when either the ICE or the electric drive is not available even if it is requested to supply propulsion power.

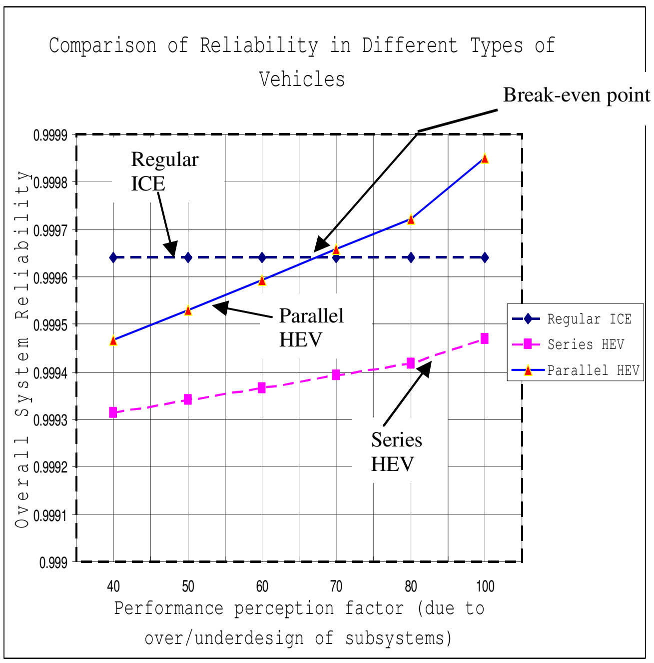


Figure 3. Comparison of System Reliability vs Performance Perception Factor in Percentage for Three Different Types of Vehicles

It is thus apparent from the above that the overall reliability numbers for series HEV is quite a bit lower than the parallel HEV, under identical situations, and it is also lower than the regular IC engine based vehicle. Overall reliability of both series and parallel HEV, without taking any graceful degradation into consideration, is of course, lower than the regular IC engine based vehicle.

With graceful degradation taken into account, parallel HEV becomes competitive with a regular IC engine based vehicle, at around 70% performance perception factor, in terms of reliability only (all these being based on our definition of perception factor and various chosen numerical values for reliability numbers). This means that some overdesign is called for on the part of the ICE (IC engine of the parallel HEV), or EVP, or both, in the parallel HEV, if one desires to have better system availability with higher user performance perception factor or index under graceful degradation conditions. Previously, this point, where a particular HEV system becomes competitive with a regular ICE based vehicle, in terms of overall reliability, was designated as the "reliability breakeven point". For series architecture, although the overall availability is higher when graceful degradation is taken into account (compared to when it is not accounted for), the availability from this architecture is still lower than the regular ICE based vehicle.

Based on the above discussion and other considerations, in general it can be inferred that:

- For regular ICE based vehicle there is no scope of graceful degradation from an architectural point of view, in terms of redundancy in propulsion. Of course, in some newer designs, it is possible to operate a vehicle with only a few of the cylinders operating (assuming the other subsystems besides the engine cylinders are functional), with proper EEC (electronic engine control) and other similar methods. But that is not within the scope of this paper.
- For series HEV there is no scope of graceful degradation, if the electric vehicle propulsion (EVP) fails.
- In both parallel and series HEV, with EVP (electric vehicle propulsion) available, some enhancement in reliability and graceful degradation mode can be achieved.
- For parallel HEV it is possible to have graceful degradation, since the vehicle can be functional with only one of the available propulsion systems, i.e. either the ICE or the electric vehicle propulsion (EVP) operating alone.
- On a different note - within electric propulsion system's power electronics itself, during partial faults, it is possible to do some amount of graceful degradation. This latter statement about operating with partial fault in the power electronic system is a different subject, with which the author has dealt elsewhere [7], and is not within the scope of this paper.

V. SUMMARY & CONCLUSIONS

As indicated in the introduction, the numerical values of reliability numbers used in this paper were used to illustrate the concepts, and the main intent of this paper is to describe a methodology for evaluating system level reliability in HEV systems, so that a proper trade-off study between various systems can be made. The methodology is provided as a tool so that system level designers can decide relative merits of different architectures. It is intended that such information on system level reliability in HEV be used together with other issues like cost and fuel economy etc. during various phases of HEV system development. It is possible to use the above methodology for various HEV systems. However, an application tool can be developed only when the various architectures for different HEV's and the exact number of components or subsystems and their interconnections are precisely known. The architectures

and precise details of interconnection varies significantly from one manufacturer to another, and until HEV standards are firmly established, it will best to leave the methodology to individual manufacturers, while trying to evaluate their system level reliability.

In this paper the author has introduced the concept of reliability and graceful degradation as they apply to the overall system level architectures in hybrid electric vehicles. Using quantitative illustrations, the comparison of different architectures has been made. It has been pointed out from a quantitative viewpoint why reliability is affected by system complexity. It has been shown that from a reliability point of view it is possible to have graceful degradation mode in a parallel HEV, such that the cumulative system reliability with graceful degradation taken into account, can exceed the reliability (or performance index) of a regular IC engine based vehicle, provided the propulsion drives are designed (or rather overdesigned) accordingly. The paper indicates that HEV allows additional degrees of freedom in design optimization from a reliability point of view. The main intent of the paper was to bring forth the importance of reliability and graceful degradation mode of operation in hybrid electric vehicles and to point out that these items are of significant implications from an overall system point of view. Of course, as has been noted earlier, the paper points to the fact that in HEV, one of the penalties for fuel economy that has to be paid, is in terms of the reliability. Once again, it should be noted that in a HEV system, reliability is but only one item among others, like fuel economy, size, cost, packaging etc., all of which should be considered in proper perspective, in order to make a product acceptable to the consumer in the long run.

VI. REFERENCES

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BIOGRAPHY

M. Abul Masrur (M'84-SM'93) received his Ph.D. in Electrical Engineering from the Texas A & M University, College Station, Texas, USA in 1984. Dr. Masrur was with the Scientific Research Labs. of the Ford Motor Co. from late 1984 to April 2001 and was involved in research and development related to simulation and control for electric drives and power electronics, advanced automotive electric energy management, electric active suspension systems for automobiles, electric power assist steering, and stand-alone UPS protection design, among other things. In April 2001, Dr. Masrur joined the US Army RDECOM-TARDEC (Research Development & Engineering Command) where he has been involved in various vehicular electric power system architecture concept design and development for military applications, cognitive electric power management, and artificial intelligence based fault diagnostics, including the 42 volt dc vehicular electrical system. He has over 65 publications, of which over 40 are in public domain international journals and conferences. Dr. Masrur also has 8 US and 3 European patents. He is a member of the Sigma Xi research society, and the Eta Kappa Nu and Tau Beta Pi honor societies in the USA. He received the Best Automotive Electronics Paper Award from the IEEE Vehicular Technology Society, USA, in 1998 for his papers in the IEEE Transactions on Vehicular Technology. Dr. Masrur is also a joint recipient of the 2006 SAE (Society of Automotive Engineers, USA) Environmental Excellence in Transportation Award - Education, Training, & Public Awareness (also known as E2T) for a tutorial he has been teaching on hybrid vehicles along with other team colleagues. Dr. Masrur is a Senior Member of the IEEE, and from 1999 to September 2007 served as an Associate Editor (Vehicular Electronics Section) of the IEEE Transactions on Vehicular Technology. He is also the current Chair of the Motor Sub-Committee (MSC) of the Electric Machinery Committee, IEEE Power & Energy Society (PES).